

UNIVERSITY OF TECHNOLOGY, SYDNEY
Faculty of Engineering and Information Technology

**MODELLING AND CONTROL OF OFFSHORE
CRANE SYSTEMS**

by

R.M.T. Raja Ismail

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

Sydney, Australia

2015

Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as a part of the requirements for other degree except as fully acknowledged within the text.

I also certify that this thesis has been written by me. Any help that I have received in my research work and in the preparation of the thesis itself has been fully acknowledged. In addition, I certify that all information sources and literature used are quoted in the thesis.

A handwritten signature in black ink, appearing to be 'R.M.T. Raja Ismail', with a stylized, looping design.

R.M.T. Raja Ismail

July 15, 2015

ABSTRACT

MODELLING AND CONTROL OF OFFSHORE CRANE SYSTEMS

by

R.M.T. Raja Ismail

Cranes are widely used in transportation, construction and manufacturing. Suspended payloads in crane system are caused to swing due to actuator movement, external disturbance such as wind flows, and motion of the crane base in the case of portable cranes. Recently, offshore cranes have become a new trend in stevedoring and in offshore construction as they can help to avoid port congestion and also to exploit ocean engineering applications. For crane operations, it is important to satisfy rigorous requirements in terms of safety, accuracy and efficiency. One of the main challenges in crane operations has been identified as the sway motion control, which is subject to underactuation of crane drive systems and external disturbances. Particularly in offshore cranes, the harsh conditions can produce exogenous disturbances during the load transfer at various scenarios of offshore crane operations in practice. Therefore, it is interesting as to how to design robust controllers to guarantee high performance in the face of disturbances and parameter variations in offshore cranes.

The motivation for this thesis is based on recent growing research interest in the derivation of dynamic models and development of control techniques for offshore cranes in the presence of, for example, the rope length variation, sway, ocean waves and strong winds in offshore crane systems. Accordingly, the work for this thesis has been conducted in the two main themes, namely analytical modelling and control design, for which new results represent its contributions.

Dynamic models of two types of offshore crane systems, namely the offshore gantry crane and offshore boom crane, are derived in the presence of vessel's ocean

wave-induced motion. The effect of wind disturbances on the payload sway is also considered in the modelling. In the control context, sliding mode control techniques for a generic form of underactuated mechanical Lagrangian systems are presented, including the conventional first-order, second-order and adaptive fuzzy sliding mode controllers. The major component in this part of the thesis is the design of sliding mode control laws based on the developed offshore crane models for trajectory tracking problems, in the presence of persistent disturbances in severe open-sea conditions. Extensive simulation results are presented to demonstrate the efficacy of the models and robustness of the designed controllers.

Acknowledgements

This thesis could not have been completed without the enormous support of numerous people. I would like to acknowledge all those people who have made contribution to the completion of my thesis.

First of all, I would like to express my sincere thanks to my PhD supervisor, Associate Professor Quang Ha, for his guidance, advice, encouragement and support in the course of my doctoral work. Regular meetings in his research group and friendly discussions during lunch time at the University of Technology, Sydney (UTS) helped me reaffirm my research direction.

I would like to take this opportunity to gratefully acknowledge Universiti Malaysia Pahang and the Ministry of Education Malaysia for the financial support of my research and study at UTS.

Most importantly, my thesis could not have been completed without the encouragement and support from my family. I would like to dedicate my thesis to my parents, Siti Khodijah and Raja Ismail, and my beloved wife Mazni and daughter Aufa, who have been a source of care, love, support and strength during my graduate study.

My brothers and sisters and many friends whose concerns and support have helped me overcome obstacles and concentrate on my study, are acknowledged. I greatly appreciate their friendship and assistance.

R.M.T. Raja Ismail
Sydney, Australia, 2015.

List of Publications

1. **R.M.T. Raja Ismail**, Nguyen D. That, Q.P. Ha (2015), *Modelling and robust trajectory following for offshore container crane systems*, “Automation in Construction” – accepted on 13 May 2015.
2. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2014), *Offshore container crane systems with robust optimal sliding mode control*, The 31st International Symposium on Automation and Robotics in Construction and Mining, Sydney, Australia, pp. 149-156.
3. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2013), *Adaptive fuzzy sliding mode control for uncertain nonlinear underactuated mechanical systems*, The 2nd International Conference on Control, Automation and Information Sciences, Nha Trang, Vietnam, pp. 212-217.
4. **R.M.T. Raja Ismail** and Q.P. Ha (2013), *Trajectory tracking and anti-sway control of three-dimensional offshore boom cranes using second-order sliding modes*, The 9th IEEE International Conference on Automation Science and Engineering, Wisconsin, Madison, USA, pp. 996-1001.
5. **R.M.T. Raja Ismail** and Q.P. Ha (2013), *Trajectory tracking control for offshore boom cranes using higherorder sliding modes*, The 30th International Symposium on Automation and Robotics in Construction and Mining, Montreal, Canada, pp. 894-904.
6. **R.M.T. Raja Ismail** and Q.P. Ha (2012), *Second-order sliding mode control for offshore container cranes*, The 22nd Australasian Conference on Robotics and Automation, Wellington, New Zealand, 7p.

7. **R.M.T. Raja Ismail**, Nguyen D. That, and Q.P. Ha (2012), *Observer-based trajectory tracking for a class of underactuated Lagrangian systems using higher-order sliding modes*, The 8th IEEE International Conference on Automation Science and Engineering, Seoul, Korea, pp. 1200-1205.
8. Nguyen D. That, Nguyen K. Quang, **R.M.T. Raja Ismail**, P.T. Nam and Q.P. Ha (2012), *Improved reachable set bounding for linear systems with discrete and distributed delays*, The 1st International Conference on Control, Automation and Information Sciences, Ho Chi Minh, Vietnam, pp. 137-141.

Contents

Certificate	ii
Abstract	iii
Acknowledgments	v
List of Publications	vi
List of Figures	xii
List of Tables	xvi
Notation	xvii
1 Introduction	1
1.1 Background	1
1.2 Research objectives	7
1.3 Thesis organization	7
2 Literature Survey	9
2.1 Underactuated mechanical system	9
2.1.1 Equations of motion	11
2.1.2 Feedback linearisation	13
2.2 Crane dynamics and control	15
2.2.1 Crane dynamics	15
2.2.2 Crane control	16
2.3 Sliding mode control	24

2.3.1	Regular form of linear-time invariant system	25
2.3.2	First-order sliding mode control	27
2.3.3	Second-order sliding mode	35
2.4	Summary	40
3	Modelling of Offshore Crane Systems	42
3.1	Introduction	42
3.2	Euler-Lagrange equation for cranes	42
3.3	Modelling of offshore gantry cranes	44
3.3.1	2-D model	44
3.3.2	3-D model	49
3.4	Modelling of offshore boom cranes	52
3.4.1	2-D model	53
3.4.2	3-D model	57
3.5	Summary	63
4	Sliding Mode Control Approaches for Underactuated Mechanical Systems with Application to Cranes	64
4.1	Introduction	64
4.2	Problem formulation	64
4.3	First-order sliding mode control	66
4.4	Adaptive fuzzy sliding mode control	67
4.4.1	Fuzzy logic control	67
4.4.2	Adaptive fuzzy sliding mode controller	68
4.4.3	Stability analysis	70
4.4.4	Results and discussion	71

4.5	Second-order sliding mode control	76
4.5.1	Second-order sliding mode controller	78
4.5.2	Second-order sliding mode observer	79
4.5.3	Observer-based 2-SMC	81
4.5.4	Results and discussion	81
4.6	Summary	88
5	Development of First-order Sliding Mode Control for Offshore Crane Systems	90
5.1	Introduction	90
5.2	Problem statement	90
5.3	Control design for 2-D offshore gantry crane	92
5.3.1	Crane trajectory	92
5.3.2	Sliding surface design using LQR approach	95
5.3.3	Sliding mode control	97
5.3.4	Results and discussion	100
5.4	Control design for 2-D offshore boom crane	110
5.4.1	Sliding surface design using LMI approach	110
5.4.2	Sliding mode control	111
5.4.3	Results and discussion	114
5.5	Summary	119
6	Development of Second-order Sliding Mode Control for Offshore Crane Systems	120
6.1	Introduction	120
6.2	Second-order sliding mode control	120

6.2.1	The control algorithm	120
6.2.2	Stability analysis	123
6.3	Results and discussion	124
6.3.1	Offshore gantry crane	124
6.3.2	Offshore boom crane	129
6.4	Summary	130
7	Thesis Contributions and Conclusions	134
7.1	Thesis contributions	134
7.2	Conclusions	135
7.3	Future work	137
	Bibliography	139

List of Figures

1.1	Panoramic view of Sydney Harbour.	2
1.2	Ships lightering operation [126].	4
1.3	An offshore crane transferring containers between a ship and a vessel [135].	4
1.4	Container gantry crane mounted on a vessel [113].	5
1.5	Ship-mounted boom cranes near Port Botany, Sydney.	5
2.1	Architecture of feedback linearisation control.	14
3.1	Motion of the offshore crane during containers transfer operation. . .	45
3.2	Motion of the offshore crane during containers transfer operation. . .	50
3.3	Motion of the 2-D offshore boom crane.	53
3.4	An offshore boom crane.	58
3.5	Motion of the offshore boom crane.	58
4.1	Two-dimensional gantry crane system at UTS laboratory.	72
4.2	Motion of the gantry crane system.	72
4.3	(a) Trolley position; (b) Sway angle; and (c) Control effort; when $d_x = d_\phi = 0$	75
4.4	(a) Trolley position; (b) Sway angle; and (c) Control effort; when $d_x \neq 0$ and $d_\phi \neq 0$	76

4.5	(a) Trolley position; (b) Sway angle; (c) Control effort; and (d) Payload mass; when $d_x \neq 0$, $d_\phi \neq 0$, and the payload mass is varied.	77
4.6	Motion of a 3D overhead gantry crane.	82
4.7	Schematic diagram of the observer-based control using second-order sliding modes for an underactuated mechanical system.	83
4.8	Sigmoid function trajectory.	84
4.9	(a) Cart position in X - and Y -directions; (b) Actual and reference trajectories.	85
4.10	Trajectory tracking error in (a) X -direction; and (b) Y -direction.	86
4.11	Swing angle projection to the (a) $Y_M Z_M$ -plane; and (b) $X_M Z_M$ -plane.	86
4.12	Real and estimated cart velocities in (a) X -direction; and (b) Y -direction.	87
4.13	Cart position with payload variation.	87
5.1	Cart position and velocity reference trajectories.	94
5.2	Hoisting rope length and velocity reference trajectories.	94
5.3	Wind drags due to (a) short burst; and (b) persistent wind disturbances.	100
5.4	Trajectory tracking responses of the (a) cart position; (b) rope length; and (c) swing angle subject to short burst wind disturbance.	101
5.5	Tracking error responses of the (a) cart position; (b) rope length; and (c) swing angle subject to short burst wind disturbance.	102
5.6	(a) Cart velocity and (b) hoist velocity responses subject to short burst wind disturbance.	103
5.7	Sliding functions subject to short burst wind disturbance.	104
5.8	(a) Cart driving force; and (b) hoisting input force subject to short burst wind disturbance.	105

5.9	Trajectory tracking responses of the (a) cart position; (b) rope length; and (c) swing angle subject to persistent wind disturbance. . .	106
5.10	Switching functions subject to persistent wind disturbance.	107
5.11	(a) Cart driving force; and (b) hoisting input force subject to persistent wind disturbance.	108
5.12	Cart position responses with nominal values of system masses and with $\Delta m_p/m_p = 10\%$	108
5.13	Rope length responses with nominal values of system masses and with $\Delta m_p/m_p = 10\%$	109
5.14	Swing angle responses with nominal values of system masses and with $\Delta m_p/m_p = 10\%$	109
5.15	Trajectory tracking responses of the (a) luff angle; (b) rope length; and (c) swing angle.	116
5.16	Tracking error responses of the (a) luff angle; (b) rope length; and (c) swing angle.	117
5.17	Sliding functions.	118
5.18	(a) Boom input torque; (b) hoisting input force.	118
6.1	Block diagram of the offshore crane control system	123
6.2	(a) Trolley position; (b) rope length; and (c) swing angles; when the mobile harbour is stationary, i.e. $\zeta = 0$ m and $\phi = \psi = 0$ rad. . . .	126
6.3	(a) Trolley position; (b) rope length; and (c) swing angles; when $\zeta = 0.02 \sin 1.25t$ m, $\phi = 0.02 \sin 1.25t$ rad and $\psi = 0.01 \sin 1.25t$ rad. . . .	127
6.4	(a) Trolley position and payload mass; (b) rope length; and (c) swing angles; when $\zeta = 0.02 \sin 1.25t$ m, $\phi = 0.02 \sin 1.25t$ rad, $\psi = 0.01 \sin 1.25t$ rad, and $\Delta m/m = 10\%$	128

6.5	(a) Slew angle; (b) luff angle; (c) rope length; and (d) swing angles; when the vessel is stationary, i.e. $\zeta = 0$ m and $\phi = \psi = 0$ rad.	131
6.6	(a) Slew angle; (b) luff angle; (c) rope length; and (d) swing angles; when $\zeta = 0.02 \sin 1.25t$ m and $\phi = \psi = 0.01 \sin 1.25t$ rad.	132
6.7	(a) Slew angle; (b) luff angle; (c) rope length; and (d) swing angles; when $\zeta = 0.02 \sin 1.25t$ m, $\phi = \psi = 0.01 \sin 1.25t$ rad, and $\Delta m/m = 10\%$	133

List of Tables

2.1	Summary of previous offshore crane models and control methods.	. . .	18
-----	--	-------	----

Nomenclature and Notation

Throughout the thesis, the following nomenclatures and notations are used:

- 1-SMC: First-order sliding mode control
- 2-SMC: Second-order sliding mode control
- 2-D: Two-dimensional
- 3-D: Three-dimensional
- AFSMC: Adaptive fuzzy sliding mode control
- DOF: Degree of freedom
- HOSM: Higher-order sliding modes
- LQR: Linear quadratic regulator
- LMI: Linear matrix inequality
- LTI: Linear time-invariant
- MIMO: Multi input multi output
- SISO: Single input single output
- SMC: Sliding mode control
- SVD: Singular value decomposition
- UMS: Underactuated mechanical system
- VSC: Variable structure control
- \mathbb{R} : Field of real numbers
- \mathbb{R}^n : n -dimensional space
- $\mathbb{R}^{n \times m}$: Space of all matrices of $(n \times m)$ -dimension
- A^T : Transpose of matrix A
- A^{-1} : Inverse of matrix A
- I_n : Identity matrix of $(n \times n)$ -dimension
- $0_{n \times m}$: Zero matrix of $(n \times m)$ -dimension
- C_θ : $\cos \theta$

- S_θ : $\sin \theta$
- $\lambda(A)$: Set of all eigenvalues of matrix A
- $\lambda_{\min}(A)$: Smallest eigenvalue of matrix A
- $\lambda_{\max}(A)$: Largest eigenvalue of matrix A
- $\text{diag}(\lambda_1, \dots, \lambda_i, \dots, \lambda_n)$: Diagonal matrix with diagonal entries λ_i , $i = 1, \dots, n$
- $\text{rank}(A)$: Rank of matrix A
- $\text{sign}(\cdot)$: Signum function
- $\|\cdot\|$: Euclidean norm of a vector or spectral norm of a matrix
- \forall : For all